# Spin effects in the fragmentation of transversely polarized and unpolarized quarks*

M. Anselmino[a], D. Boer[b], U. D'Alesio[c] and F. Murgia[c]

[a] *Dipartimento di Fisica Teorica, Università di Torino and INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*

[b] *RIKEN-BNL Research Center Brookhaven National Laboratory, Upton, NY 11973, USA*

[c] *Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari and Dipartimento di Fisica, Università di Cagliari C.P. 170, I-09042 Monserrato (CA), Italy*

**Abstract.** We study the fragmentation of a transversely polarized quark into a non collinear ($\boldsymbol{k}_\perp \neq 0$) spinless hadron and the fragmentation of an unpolarized quark into a non collinear transversely polarized spin 1/2 baryon. These nonperturbative properties are described by spin and $\boldsymbol{k}_\perp$ dependent fragmentation functions and are revealed in the observation of single spin asymmetries. Recent data on the production of pions in polarized semi-inclusive DIS and long known data on $\Lambda$ polarization in unpolarized $p$–$N$ processes are considered: these new fragmentation functions can describe the experimental results and the single spin effects in the quark fragmentation turn out to be surprisingly large.

## INTRODUCTION

Several large and puzzling single spin asymmetries in high energy inclusive processes are experimentally well known since a long time and new ones have just been or are being measured. These effects are absent in massless perturbative QCD dynamics and they depend on new and interesting aspects of nonperturbative QCD; as such, they deserve a careful study, both theoretically and experimentally.

We consider here spin properties of quark fragmentation processes, which have been suggested in the literature [1–3], and address the question of whether or not they might explain some single spin asymmetries observed in inclusive processes: in particular we look at the recently observed azimuthal dependence of the number

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of pions produced in polarized semi-inclusive DIS, $\ell p^\uparrow \to \ell \pi X$ [4,5], and at the longstanding problem of the polarization of $\Lambda$'s produced in unpolarized $p$–$p$ and $p$–$n$ interactions, $pN \to \Lambda^\uparrow X$ [6]. Both these unexpected spin dependences should originate in the fragmentation process of a quark, polarized in the first case ($q^\uparrow \to \pi X$) and unpolarized in the second one ($q \to \Lambda^\uparrow X$).

## QUARK ANALYSING POWER

The inclusive production of hadrons in DIS with transversely polarized nucleons, $\ell N^\uparrow \to \ell h X$, is the ideal process to study the so-called Collins effect, *i.e.* the spin and $\boldsymbol{k}_\perp$ dependence of the fragmentation process of a transversely polarized quark, $q^\uparrow \to hX$. In such a case, in fact, possible effects in quark distribution functions [7], which require initial state interactions [8,9], are expected to be negligible.

If one looks at the $\gamma^* N^\uparrow \to hX$ process in the $\gamma^*$–$N$ c.m. frame, the elementary interaction is simply a $\gamma^*$ hitting head on a transversely polarized quark, which bounces back and fragments into a jet containing the detected hadron. The hadron $\boldsymbol{p}_T$ in this case coincides with its $\boldsymbol{k}_\perp$ inside the jet; the fragmenting quark polarization can be computed from the initial quark one.

The spin and $\boldsymbol{k}_\perp$ dependent fragmentation function for a quark with momentum $\boldsymbol{p}_q$ and a *transverse* polarization vector $\boldsymbol{P}_q$ ($\boldsymbol{p}_q \cdot \boldsymbol{P}_q = 0$) which fragments into a hadron with momentum $\boldsymbol{p}_h = z\boldsymbol{p}_q + \boldsymbol{p}_T$ ($\boldsymbol{p}_q \cdot \boldsymbol{p}_T = 0$) can be written as:

$$D_{h/q}(\boldsymbol{p}_q, \boldsymbol{P}_q; z, \boldsymbol{p}_T) = \hat{D}_{h/q}(z, p_T) + \frac{1}{2}\,\Delta^N D_{h/q^\uparrow}(z, p_T)\,\frac{\boldsymbol{P}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_T)}{|\boldsymbol{p}_q \times \boldsymbol{p}_T|} \tag{1}$$

where $\hat{D}_{h/q}(z, p_T)$ is the unpolarized fragmentation function. Notice that – as required by parity invariance – the only component of the polarization vector which contributes to the spin dependent part of $D$ is that perpendicular to the $q-h$ plane; in general one has:

$$\boldsymbol{P}_q \cdot \frac{\boldsymbol{p}_q \times \boldsymbol{p}_T}{|\boldsymbol{p}_q \times \boldsymbol{p}_T|} = P_q \sin\Phi_C\,, \tag{2}$$

where $P_q = |\boldsymbol{P}_q|$ and we have defined the *Collins angle* $\Phi_C$.

When studying single spin asymmetries one considers differences of cross-sections with opposite transverse spins; by reversing the nucleon spin all polarization vectors, including those of quarks, change sign and the quantity which eventually contributes to single spin asymmetries is:

$$D_{h/q}(\boldsymbol{p}_q, \boldsymbol{P}_q; z, \boldsymbol{p}_T) - D_{h/q}(\boldsymbol{p}_q, -\boldsymbol{P}_q; z, \boldsymbol{p}_T) = \Delta^N D_{h/q^\uparrow}(z, p_T)\,\frac{\boldsymbol{P}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_T)}{|\boldsymbol{p}_q \times \boldsymbol{p}_T|} \tag{3}$$

which implies the existence of a *quark analysing power* for the fragmentation process $q \to h + X$:

$$A_q^h(\boldsymbol{p}_q, \boldsymbol{P}_q; z, \boldsymbol{p}_T) = \frac{D_{h/q}(\boldsymbol{p}_q, \boldsymbol{P}_q; z, \boldsymbol{p}_T) - D_{h/q}(\boldsymbol{p}_q, -\boldsymbol{P}_q; z, \boldsymbol{p}_T)}{D_{h/q}(\boldsymbol{p}_q, \boldsymbol{P}_q; z, \boldsymbol{p}_T) + D_{h/q}(\boldsymbol{p}_q, -\boldsymbol{P}_q; z, \boldsymbol{p}_T)} \tag{4}$$
$$= \frac{\Delta^N D_{h/q^\uparrow}(z, p_T)}{2\,\hat{D}_{h/q}(z, p_T)} \, \frac{\boldsymbol{P}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_T)}{|\boldsymbol{p}_q \times \boldsymbol{p}_T|} \equiv A_q^h(z, p_T) \, \frac{\boldsymbol{P}_q \cdot (\boldsymbol{p}_q \times \boldsymbol{p}_T)}{|\boldsymbol{p}_q \times \boldsymbol{p}_T|} \cdot$$

This results in a single spin asymmetry [10]:

$$A_N^h(x, y, z, \Phi_C, p_T) = \frac{d\sigma^{\ell+p,\boldsymbol{P} \to \ell+h+X} - d\sigma^{\ell+p,-\boldsymbol{P} \to \ell+h+X}}{d\sigma^{\ell+p,\boldsymbol{P} \to \ell+h+X} + d\sigma^{\ell+p,-\boldsymbol{P} \to \ell+h+X}}$$
$$= \frac{\sum_q e_q^2 \, h_{1q}(x) \, \Delta^N D_{h/q}(z, p_T)}{2 \sum_q e_q^2 \, f_{q/p}(x) \, \hat{D}_{h/q}(z, p_T)} \, \frac{2(1-y)}{1+(1-y)^2} \, P \, \sin\Phi_C \,, \tag{5}$$

where $P$ is the transverse (with respect to the $\gamma^*$ direction) proton polarization.

We wonder how large the quark analysing power can be. Such a question has been addressed in Ref. [10], where recent data on $A_N^\pi$ [4,5] were considered. We refer to that paper for all the details and only outline the main procedure here. Under some realistic assumptions and using isospin and charge conjugation invariance Eq. (5) gives ($i = +, -, 0$):

$$A_N^{\pi^i}(x, y, z, \Phi_C, p_T) = \frac{h_i(x)}{f_i(x)} \, A_q^\pi(z, p_T) \, \frac{2(1-y)}{1+(1-y)^2} \, P \, \sin\Phi_C \tag{6}$$

where:

$$i = + : \quad h_+ = 4h_{1u} \qquad f_+ = 4f_{u/p} + f_{\bar{d}/p} \tag{7}$$
$$i = - : \quad h_- = h_{1d} \qquad f_- = f_{d/p} + 4f_{\bar{u}/p} \tag{8}$$
$$i = 0 : \quad h_0 = 4h_{1u} + h_{1d} \qquad f_0 = 4f_{u/p} + f_{d/p} + 4f_{\bar{u}/p} + f_{\bar{d}/p} \,. \tag{9}$$

The $f$'s are the unpolarized distribution functions and the $h_1$'s are the transversity distributions. Notice that the above equations imply – at large $x$ values – $A_N^{\pi^+} \simeq A_N^{\pi^0}$ as observed by HERMES [11].

We bound the unknown transversity distributions saturating Soffer's inequality [12]

$$|h_{1q}| \leq \frac{1}{2} \, (f_{q/p} + \Delta q) \,, \tag{10}$$

and, by comparing with SMC data [5]

$$A_N^{\pi^+} \simeq -(0.10 \pm 0.06) \, \sin\Phi_C \,, \tag{11}$$

we obtain the significant lower bound for pion valence quarks:

$$|A_q^\pi(\langle z \rangle, \langle p_T \rangle)| \gtrsim (0.24 \pm 0.15) \qquad \langle z \rangle \simeq 0.45 \,, \quad \langle p_T \rangle \simeq 0.65 \, \mathrm{GeV}/c \,. \tag{12}$$

A similar result is obtained by using HERMES data [4], although their transverse polarization is much smaller. These lower bounds of the quark analysing power are remarkably large and indeed the Collins mechanism might be (at least partly) responsible for several other observed single transverse spin asymmetries [8].

## QUARK POLARIZING FRAGMENTATION FUNCTIONS

We consider now the possibility that an unpolarized quark fragments into a transversely polarized hadron [2,3]; in analogy to Eq. (1) we write

$$\hat{D}_{h^\uparrow/q}(z, \boldsymbol{k}_\perp) = \frac{1}{2}\, \hat{D}_{h/q}(z, k_\perp) + \frac{1}{2}\, \Delta^N D_{h^\uparrow/q}(z, k_\perp)\, \frac{\hat{\boldsymbol{P}}_h \cdot (\boldsymbol{p}_q \times \boldsymbol{k}_\perp)}{|\boldsymbol{p}_q \times \boldsymbol{k}_\perp|} \tag{13}$$

for an unpolarized quark with momentum $\boldsymbol{p}_q$ which fragments into a spin 1/2 hadron $h$ with momentum $\boldsymbol{p}_h = z\boldsymbol{p}_q + \boldsymbol{k}_\perp$ and polarization vector along the $\uparrow = \hat{\boldsymbol{P}}_h$ direction. $\Delta^N D_{h^\uparrow/q}(z, k_\perp)$ (denoted by $D_{1T}^\perp$ in Ref. [2]) is a new *polarizing fragmentation function*.

This reflects into a possible polarization of hadrons inclusively produced in the high energy interaction of unpolarized nucleons. Indeed, it is well known since a long time that $\Lambda$ hyperons produced with $x_F \gtrsim 0.2$ and $p_T \gtrsim 1$ GeV/$c$ in the collision of two unpolarized nucleons are polarized perpendicularly to the production plane, as allowed by parity invariance; a huge amount of experimental information, for a wide energy range of the unpolarized beams, is available on such single spin asymmetries [6]:

$$P_\Lambda = \frac{d\sigma^{pN\to\Lambda^\uparrow X} - d\sigma^{pN\to\Lambda^\downarrow X}}{d\sigma^{pN\to\Lambda^\uparrow X} + d\sigma^{pN\to\Lambda^\downarrow X}}\,\cdot \tag{14}$$

By taking into account intrinsic $\boldsymbol{k}_\perp$ in the hadronization process, and assuming that the factorization theorem holds also when $\boldsymbol{k}_\perp$'s are included [1], one obtains

$$\begin{aligned} \frac{E_\Lambda\, d^3\sigma^{pN\to\Lambda X}}{d^3\boldsymbol{p}_\Lambda}\, P_\Lambda = \sum_{a,b,c,d} \int \frac{dx_a\, dx_b\, dz}{\pi z^2}\, d^2\boldsymbol{k}_\perp\, f_{a/p}(x_a)\, f_{b/N}(x_b) \\ \times\, \hat{s}\, \delta(\hat{s} + \hat{t} + \hat{u})\, \frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}}(x_a, x_b, \boldsymbol{k}_\perp)\, \Delta^N D_{\Lambda^\uparrow/c}(z, \boldsymbol{k}_\perp) \end{aligned} \tag{15}$$

We use the above equation, together with a simple parameterization of the polarizing fragmentation functions, to see whether or not one can fit the experimental data on $\Lambda$ and $\bar{\Lambda}$ polarization. All details can be found in Ref. [3] and some results are shown here in Fig. 1.

The data can be described with remarkable accuracy in all their features: the large negative values of the $\Lambda$ polarization, the increase of its magnitude with $x_F$, the puzzling flat $p_T \gtrsim 1$ GeV/$c$ dependence and the $\sqrt{s}$ apparent independence; data from $p$–$p$ processes are in agreement with data from $p$–$Be$ interactions and also the tiny or zero values of $\bar{\Lambda}$ polarization are well reproduced. The resulting functions $\Delta^N D_{\Lambda^\uparrow/q}$ are very reasonable and realistic.

We conclude by stressing that a systematic phenomenological approach towards the description and prediction of single transverse spin asymmetries, based on perturbative QCD dynamics and nonperturbative quark properties, is now possible and worth being developed.

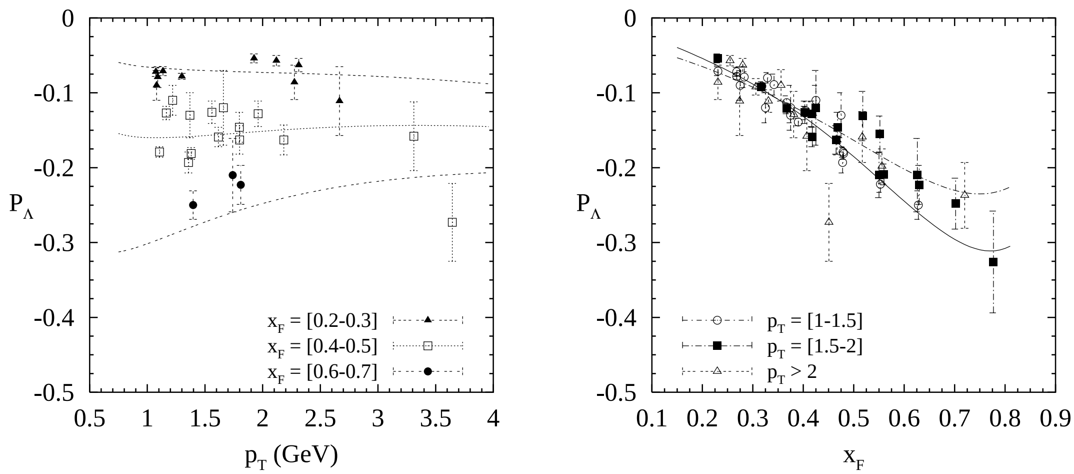


**FIGURE 1.** Our best fit to $P_\Lambda$ data from $p$–$Be$ reactions (a partial collection from Ref. [6]) as a function of $p_T$ (on the left) and of $x_F$ (on the right). For each $x_F$-bin, the corresponding theoretical curve is evaluated at the mean $x_F$ value in the bin. The two theoretical curves, on the right, correspond to $p_T = 1.5$ GeV/$c$ (solid) and $p_T = 3$ GeV/$c$ (dot-dashed).

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